Excavating a Buried Higgs

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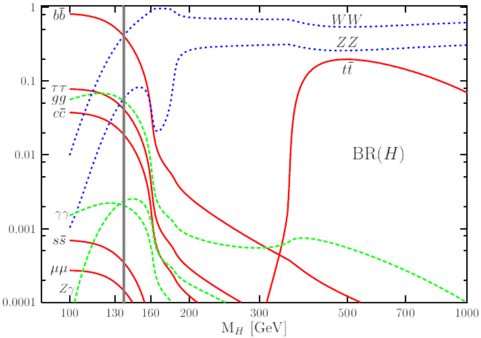
A light Higgs at the LHC

- A light Standard Model Higgs is a challenging signal at the LHC:

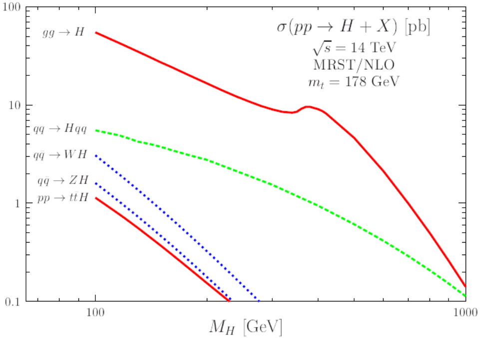


SM BRs as a function of m_h

$m_h < 135$ GeV : $h \to b\bar{b}$

- QCD backgrounds for a dominant hadronic decay mode are immense.

Strategies for a light Higgs



- $gg \to h$, $qq \to hqq$: a hadronic h leads to difficult all-hadronic final states
- $V + h$, $t\bar{t} + h$: better, but backgrounds $V+$ jets, $t\bar{t}+$ jets are still very large
- jet substructure: tools capable of digging a hadronic h out of the QCD radiation

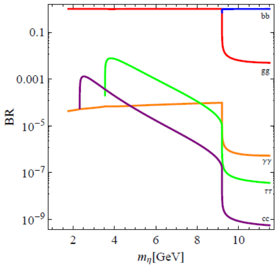
A light SM-like Higgs is *narrow*

- Small matter Yukawas: $\Gamma_h(m_h = 120\text{ GeV}) = 3.7\text{ MeV}$
- $\Rightarrow$ New physics coupling to H can easily change branching fractions by $\mathcal{O}(1)$, with minimal changes to EWSB
- For example: $\Delta\mathcal{L} = \lambda_s |H|^2 s^2$
  - $\Gamma(h \to ss) \sim m_h \frac{\lambda_s^2}{\lambda_h^2}$; $\Gamma(h \to b\bar{b}) \sim m_h y_b^2$
  - large range of parameter space: $BR(h \to ss) > BR(h \to b\bar{b})$
  - final state then depends on $BR(s \to X)$'s
- Theoretically appealing: reduce tuning in Higgs potential, utilize portal to hidden sectors
- Relatively easy to achieve: should be prepared to cover parameter space at LHC

Buried Higgs

- A reference model explicitly realizing interesting scenarios for both LEP and LHC
- "Double protection": a SUSY little Higgs Bellazzini, Csáki, Falkowski, Weiler, '09
- H_d, H_u, a: PNGBs with loop-generated masses
- a is naturally light (few GeV) and couples to SM fermions through mixing with heavy vector-like partners of third-generation fermions

- Dominant decay $a \longrightarrow gg$
- Limits and discovery:
  - current limits from LEP: $m_h \gtrsim 86$ GeV
  - what about the LHC?



Buried Higgs at LHC

- Search strategies for $h \to aa \to 4X,\ 2X2Y$ depend critically on
  - m_a: separation of decay products
  - $BR(a \to 2X)$: especially to non-hadronic ($\gamma\gamma,\ \mu\mu,\ \tau\tau$) or taggable ($bb$, $\tau\tau$) final states
- $h \to aa$ discovery is easiest when:
  - isolated taggable decay products in final state (*e.g.*, $4b$)

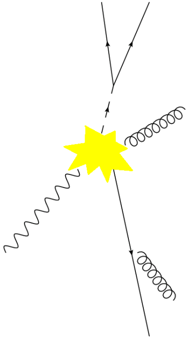
    Cheung, Song, Yan, '07; Carena et al., '07
  - or *BR*s to rare clean decay modes are not too suppressed

    Dobrescu, Landsberg, Matchev, '00; Chang, Fox, Weiner, '06; Lisanti, Wacker '08
- Light a and suppressed BRs to non-hadronic final states put a buried Higgs out of reach with these approaches
- To take full advantage of LHC discovery potential we must develop discovery techniques for the dominant all-hadronic decay mode $h \to aa \to 4g$

Studying new physics with jets

- LHC is a busy hadronic environment with multiple hard scales: $\sqrt{s} \gg M \gg \Lambda_{QCD}$. Essential elements of boosted analyses include:

1. ability to resolve events on multiple angular scales
2. variables to discriminate between QCD shower and collimated hard decays
3. algorithm to reduce contamination from unrelated soft radiation



Studying new physics with jets

- LHC is a busy hadronic environment with multiple hard scales: $\sqrt{s} \gg M \gg \Lambda_{QCD}$. Essential elements of boosted analyses include:

- ability to resolve events on multiple angular scales
  - Sequential jet algorithms:

$$
\begin{aligned}
d_{ij} &= \min(p_{Ti}^n, p_{Tj}^n)\frac{\Delta R_{ij}}{R_{cut}} \\
d_i &= p_{Ti}^n \\
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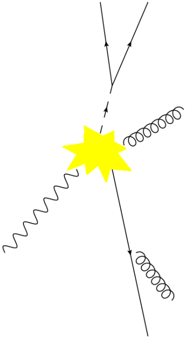
\end{aligned}
$$



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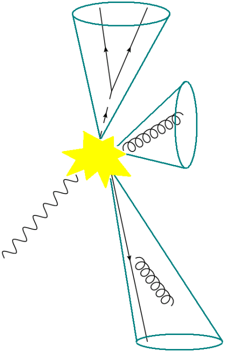

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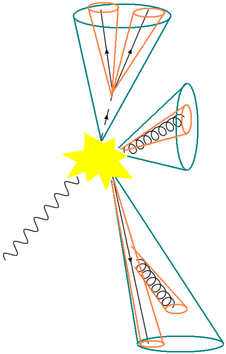


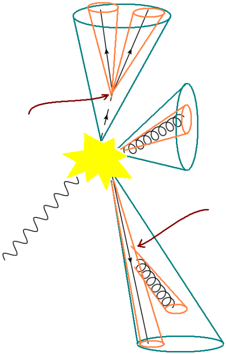
Studying new physics with jets

- LHC is a busy hadronic environment with multiple hard scales: $\sqrt{s} \gg M \gg \Lambda_{QCD}$. Essential elements of boosted analyses include:

- variables to discriminate between QCD shower and collimated hard decays
  - Specialize to specific search and backgrounds
  - a few examples, defined for a splitting $j \to j_1, j_2$:
  - Energy sharing: $z = \min(E_1, E_2)/E$

    Thaler, Wang '08
  - Mass drop: $\max(m_1, m_2) < \mu m_j$

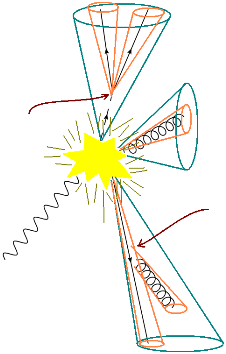
    Butterworth, Davison, Rubin, Salam '08



Studying new physics with jets

- LHC is a busy hadronic environment with multiple hard scales: $\sqrt{s} \gg M \gg \Lambda_{QCD}$. Essential elements of boosted analyses include:

- algorithm to reduce contamination from unrelated soft radiation
  - contribution scales like ΔR^2: especially important for large jets
  - filtering Butterworth, Davison, Rubin, Salam ‘08
  - pruning Ellis, Vermilion, Walsh ‘09
  - trimming Krohn, Thaler, Wang ‘09



- Thoughtful use of jet algorithms changes S, B.

Jet substructure and the Higgs

- Jet substructure can rescue the utility of hadronic Higgs decay modes Butterworth, Davison, Rubin, Salam '08
- In the standard model: $pp \to V + (h \to b\bar{b})$
  1. leptonic decays of V: allow initial event identification and selection
  2. Go to boosted regime: improve S/B
  3. Look for substructure to differentiate collimated H decays from QCD radiation
  4. Groom jets: minimize contribution from unrelated soft radiation to improve mass resolution
  5. Utilize b-tags to further suppress QCD background

Jet substructure and the Higgs

2. Go to boosted regime: improve S/B

- Different scaling of signal and background in boosted regime:
  - signal: $m_{b\bar{b}}$ fixed, $\Delta R_{b\bar{b}} \sim m_{b\bar{b}}/p_{Tb\bar{b}}$
  - background: for a given ΔR_{jj}, $m_{jj} \propto p_{Tjj}\Delta R_{jj}$
  - large p_T: signal has large $m_{b\bar{b}}$ and small $\Delta R_{b\bar{b}}$
    background, large $m_{b\bar{b}}$ and large $\Delta R_{b\bar{b}}$
- in boosted regime, h collected in single fat jet ($R \simeq 1$–1.5)
- Cluster events initially on large angular scales

Jet substructure and the Higgs

3. Look for substructure to differentiate collimated H decays from QCD radiation

- Resolve fat jet on finer angular scales looking for a hard splitting characteristic of a boosted hard decay:
  - Can choose R_{eff} event by event using a sequential declustering procedure Butterworth, Davison, Rubin, Salam '08: determine R_{eff} from the first sufficiently interesting splitting in the sequence
    - For each splitting, $j \to j_1, j_2$,
    - if the splitting has a large *mass drop*, $\max(m_1, m_2) < \mu m_j$,
    - and is *symmetric*, $y \equiv \frac{\min(p_{T1}^2, p_{T2}^2)}{m_j^2} \Delta R_{12}^2 > y_{cut}$,
    - stop: have found a Higgs candidate at $R_{eff} = \Delta R_{12}$. Else, keep unclustering the more massive jet.
  - We will use a fixed angular scale for subjets.
  - We will still look for a light scale and a symmetric decay

Jet substructure and the Higgs

4. Groom jets: minimize contribution from unrelated soft radiation to improve mass resolution

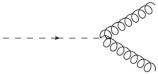
    - Soft contamination distorts jet properties and in particular invariant mass; success of analysis relies on being able to reconstruct signal mass peak well
    - We will use trimming Krohn, Thaler, Wang '09 to clean up our jets

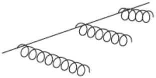
5. Utilize *b*-tags to further suppress QCD background

    - Even after these jet gymnastics QCD backgrounds are still huge.
    - Requiring 2 *b*-tags reduces SM background by more than an order of magnitude.

Boosted BSM $h \to 4g$

- $h \to aa \to 4g$ looks like $h \to j_a j_a$ at LHC energies: do not resolve $a \to gg$ splitting
- This is a similar topology to SM. But no b tags. Are we dead?
- "a-tagging": a boosted a does not look like a generic QCD jet
  - new jet variables to distinguish j_a from QCD radiation
  - less radiation

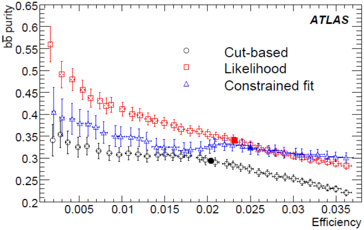




  - presence of *small* mass scale $m_a \ll p_{Ta}$

Boosted BSM $h \to 4g$

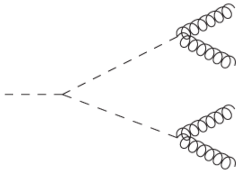
- For non-SM Higgs, $t\bar{t}h$ production channel becomes relatively more useful:
  - SM: in addition to large $t\bar{t} + jj$ background, severe combinatoric background: $t\bar{t} \to b\bar{b}WW$



total signal efficiency and purity for different approaches to the combinatorics (ATLAS TDR)

  - non-SM: with leptonic tops, can cleanly separate top and Higgs decay products
  - $\Rightarrow$ have additional independent production channel available

Distinguishing a Higgs jet from a QCD jet



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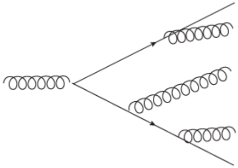
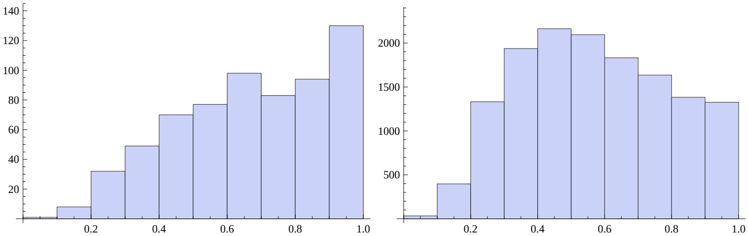


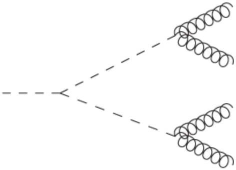
- As in SM, start with jet clustered on large scale to select initial Higgs candidate
- resolve on finer angular scales to distinguish properties
- look for evidence of hard splitting to 2 particles with identical mass:
    - require 2 subjets with $p_{Ti} > f_i \, p_{T,tot}$
    - "mass democracy": $\alpha \equiv \min\left[\frac{m_{j1}}{m_{j2}}, \frac{m_{j2}}{m_{j1}}\right] > \alpha_{cut}$

Distinguishing a Higgs jet from a QCD jet



- signal and background distributions of α in $t\bar{t} + h$ after requiring $p_T > 125$ GeV

Distinguishing a Higgs jet from a QCD jet



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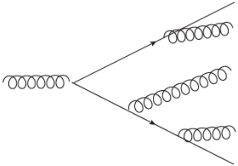
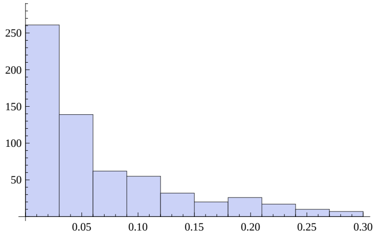


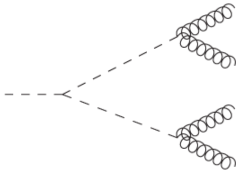
- Only final stage of signal cascade decay involves colour sources: low mass and small angle
- $\Rightarrow$ expect minimal radiation between subjets see also: Galliccio, Schwartz, '10
- *colour flow*: $\beta = \frac{p_{Tj_3}}{p_{Tj}} < \beta_{cut}$
  - definition with single jet: reduce sensitivity to pileup
- sensitivity depends on p_T threshold for soft jets

Distinguishing a Higgs jet from a QCD jet



- signal and background distributions of β in $t\bar{t} + h$ after requiring $p_T > 125$ GeV; $p_{T,soft} > 1$ GeV

Distinguishing a Higgs jet from a QCD jet



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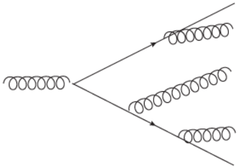
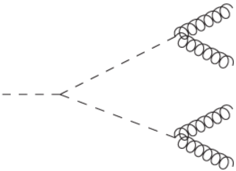


- Select moderately or highly boosted Higgs to control backgrounds (physics or combinatorics)
- $\Rightarrow$ QCD jets passing cuts have likewise hard p_T spectrum
- QCD: $\langle m^2 \rangle = \frac{\alpha_s C_F}{\pi} p_T^2 R^2 + \ldots$
- require $(m_{j1} + m_{j2})/2 < m_{cut}$

Distinguishing a Higgs jet from a QCD jet



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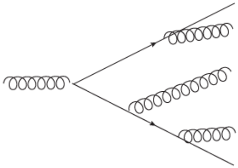


- Some further possibilities:
  - Track counting: low-scale gluon-initiated jets are comparatively track-sparse, and track counting may be an efficient discriminant
  - Resolving $a \rightarrow gg$: If it is possible to resolve perturbative splitting $a \rightarrow gg$, this additional substructure variable can help distinguish between the collimated a and the more hierarchical background Chen, Nojiri, Sreethawong '10
- While promising, will not include in results

Results

A few notes about event generation:

- Signal and background processes are generated with MadGraph/MadEvent for $t\bar{t}h$ and in Pythia for $W+h$ and showered with Pythia (k_T-ordered); clustering is done using FastJet with some additional clustering done in Mathematica
- Include pile-up and underlying event
- For $t\bar{t}h$: main backgrounds $V+j$, $t\bar{t}+jj$ are matched using MadGraph's native k_T-MLM procedure
- Results robust under changing model of parton shower (Pythia Q^2-ordered) and choice of matching scheme (shower-k_T)
- Also consider subdominant backgrounds (for $t\bar{t}h$: $t\bar{t}Z$, $Z+jj$)

Results: $t\bar{t}h$

A few notes about event generation:

- 3 signal samples: $m_h = 80$ GeV, 100 GeV , 120 GeV,
  - $m_a = 8$ GeV
- develop two sets of cuts, for $m_h = 120$ GeV and $m_h \leq 100$ GeV
- Assume SM production cross sections and 100% BR to $4g$ final state

Cut flow for $t\bar{t} + h$: preselection

	σ_{sig} (fb)	σ_{bkgd} (fb)	S/B	$S/\sqrt{B}$ at 100 fb^{-1}
preselection	8.1	6700	1.2×10^{-3}	1.0

- Select for top decay products: 2 b, 2 ℓ, MET; leptonic Z-window veto; jets found with anti-k_T, $R = 0.4$
- Model b tagging efficiency with simple 0.6 flat tagging rate
- cluster jets with $p_T > 10$ GeV with $R = 1.5$;
- trim fat jets: drop $R = 0.4$ subjets with $p_T < 0.15\, p_{T,tot}$
- Higgs candidate is the hardest fat jet in the event.

Cut flow for $t\bar{t} + h$: kinematics and substructure

	σ_{sig} (fb)	$\sigma_{bkgd}(fb)$	S/B
preselection	8.1	6700	1.2×10^{-3}
kinematics	1.7	220	7.8×10^{-3}
mass democracy	0.96	76	1.2×10^{-2}

- look at hard fat jets: $p_T > 125$ GeV,
- which contain hard subjets: $j \supset j_1, j_2$ with $p_T > 40$ GeV
- mass democracy cut on hardest subjets: $\alpha(j_1, j_2) > 0.70$

Cut flow for $t\bar{t} + h$: colour cuts

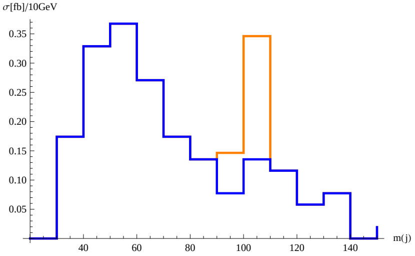
	σ_{sig} (fb)	$\sigma_{bkgd}(fb)$	S/B
subjet kinematics	0.96	76	1.2×10^{-2}
$\beta < 0.03$	0.43	17	2.6×10^{-2}

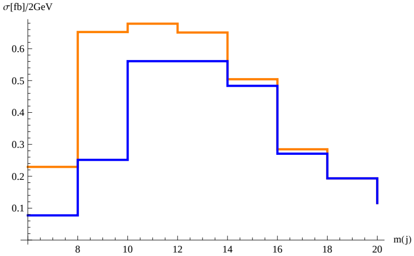
- Colour flow: consider set of $R = 0.4$ subjets within $R = 1.5$ of jet centroid
  - consider two different thresholds for soft jets: 5 GeV and 1 GeV
  - best results (shown here): p_T thresholds at 1 GeV
  - good results for β cut at $p_T > 5$ GeV
- require $\beta(j_3) < 0.03$

Cut flow for $t\bar{t}h$: mass window cuts

	σ_{sig} (fb)	σ_{bkgd} (fb)	S/B	$S/\sqrt{B}$ (100 fb^{-1})
colour flow	0.43	17	2.6×10^{-2}	1.1
subjet mass	0.28	1.9	0.14	2.0
Higgs window	0.28	0.21	1.3	6.1

- jet mass: require $|m_j - m_h| < 10$ GeV
- subjet mass: require $(m_1 + m_2)/2 < 10$ GeV





Background in blue, signal plus background in orange

Results: $W + h$

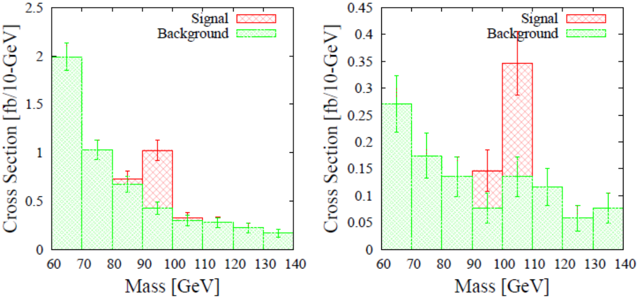
- Similar cuts for $W + h$ channel: parameters adjusted for different kinematics of final state
- Preselection: cluster event on large scale, $R = 1.0$ for $m_h = 100$ GeV, and ask for
  - a hard jet: $p_T > 200$ GeV
  - a lepton from the W
- Resolve subjets on the finer scale $R = 0.3$.
- Impose subjet cuts on the 2 hardest subjets:
  - mass democracy $\alpha < 0.7$
  - colour flow $\beta < 0.005$
  - subjet mass cut $\bar{m} < 10$ GeV
  - For mass cuts, trim subjets using $f = 0.03$

Results: $W + h$

	σ_{sig} (fb)	σ_{bg} (fb)	S/B	$S/\sqrt{B}$
$p_T(j) > 200$ GeV	16	30000	5.2×10^{-3}	0.9
subjet mass	12	19000	6.2×10^{-3}	0.9
Higgs window	7.1	400	1.8×10^{-2}	3.6
$\alpha > 0.7$	4.1	140	3.0×10^{-2}	3.5
$\beta < 0.005$, $p_T^{\min} = 1$ GeV	0.67	0.74	0.90	7.8
$\beta < 0.005$, $p_T^{\min} = 5$ GeV	2.9	2.6	0.11	5.7

results are again for 100 fb $^{-1}$

Combining channels



Reconstructed h mass in the $W+$ jets (left) and $t\bar{t}+$ jets channels (right). Error bars show statistical errors.

Combining channels

- Results for Higgses above and below 114 GeV in both channels:

		$m_h = 80$ GeV	$m_h = 100$ GeV	$m_h = 120$ GeV
$W + h$	$S/\sqrt{B}$	6.6 (4.8)	7.8 (5.7)	7.0 (6.9)
	S/B	0.34 (0.067)	0.90 (0.11)	0.80 (0.24)
$t\bar{t} + h$	$S/\sqrt{B}$	6.1 (5.9)	6.1 (5.7)	7.1 (7.1)
	S/B	1.1 (0.97)	1.3 (1.1)	2.5 (2.5)

- Numbers outside (inside) parentheses are for soft radiation thresholds 1 (5) GeV
- Without colour flow cut: 3σ
- Cuts are optimized for $m_h \leq 100$ GeV and $m_h = 120$ GeV separately.

Conclusions

- A light Higgs, even if not below LEP limit, can easily decay to a complicated multi-particle final state which can be challenging at the LHC.
- A light Higgs with dominant non-Standard Model decay mode $h \to 4g$ can be discovered at the LHC
- Two useful production channels: $V + h$ and $t\bar{t} + h$
    - $t\bar{t}h$ relatively more useful for BSM Higgses than SM Higgses: combinatoric background ameliorated
- Colour flow observables have promise to extend LHC BSM sensitivity, both in other Higgs searches and beyond